PRIUS GEN IV 1.8L PERFORMANCE SIMULATION

http://www.leapcad.com/Transportation/Prius_Gen_IV_1.8L_Simulation.mcd

Macro Model of Hybrid Vehicle Performance: Prius

T.icem2Procedure:

First model the Prius Internal Combustion Engine's (ICE) and the motor's, torque and power. Define vehicle and road parameters.

MG1 Starter and Controller Acceleration Protocol:

MG1 is the battery initiated starter for the ICE. "Simulate" MG1's spin startup, $\Omega1init_{m2}$ and $\Omega1init_{ice}$, as a ramp from 0 to its maximum speed, along with the motor M2 and ICE, respectively, which are also driven by the Prius Controller to ramp up. Refer to Startup Curves on bottom of page 6. This is an arbitrary set of conditions just to start the generator turning. Note that this startup is not a function of time, but of corresponding rotations. This startup condition simulates a low gear mode for the ICE.

Evaluate two different Prius Control Strategies: Max Acceleration and Nominal. See curves on page 4.

During acceleration, the largest torque is from motor/generator MG2, which is geared to the axle. The axle determines the vehicle speed. Use the MG2 rotation, ω_{m2}, as our control variable. During acceleration, supply peak electrical power to MG2 from both the battery (peak battery power for 10 seconds) and from MG1, which is now run as a generator at it's max speed and is mechanically driven by the ICE.

As MG2 speeds up and demands increasing power, throttle back it's peak drive/torque by limiting the MG2's electrical power input to the peak Inverter Output, i.e. the sum of the battery's and MG1 generator's peak power. Refer to the curve of M2 Torque vs.ω_{m2} on page 3.

Peak acceleration and 0 - 60 mph is programmed by setting the MG1 max speed: Ωmax_{m1}

Use equations for vehicle dynamics to calculate the time to 60 mph. Plot performance simulation curves. Calculate All Electric Range, AER, miles from a single charge of the battery. Calculate AER using various EPA driving modes.

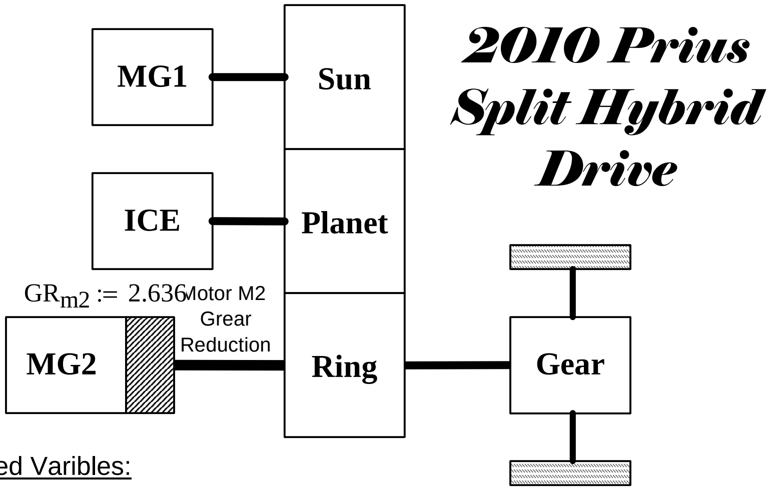
Compare Prius Performance to GM Volt.

Basic Description of Prius
http://en.wikipedia.org/wiki/Toyota_Prius

Modeling and Simulation of Serial Parallel Hybrid EV
http://www.mekatro.com/pdf/Eleco05_SPHEV.pdf

Description and Design of Synergy (Planetary Gear) Drive
http://autos.yahoo.com/green_center-article_24/ Patent:US6005297

www.springerlink.com/index/DL1Q76921M22P7ML.pdf



$GR_{m2} := 2.636$

Rotation Speed Varibles:

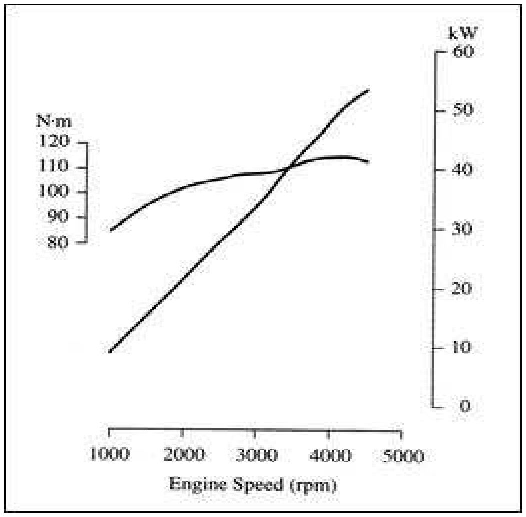
MG1, MG2, and Engine: ωm1, ωm2, and ωice.

Power Efficiencies:

Inverter, axle to tire, engine to MG1, reduction gear, and engine to axle

efficiencies ηinv, ηaxle, ηeng_m1, ηred, and ηaeng_axle

Prius Gen III ICE Performance Curves



Scale the Power and Torque Models for Toyota Atkinson Gen III 1.5L ICE to Gen IV 1.8L

Match Model Parameters to: **[Specifications for Different Prius Models](http://www.leapcad.com/Transportation/Toyota_Prius_Model_Specifications.pdf)**

http://www.leapcad.com/Transportation/Toyota_Prius_Model_Specifications.pdf

Generation III Torque and Power Models:

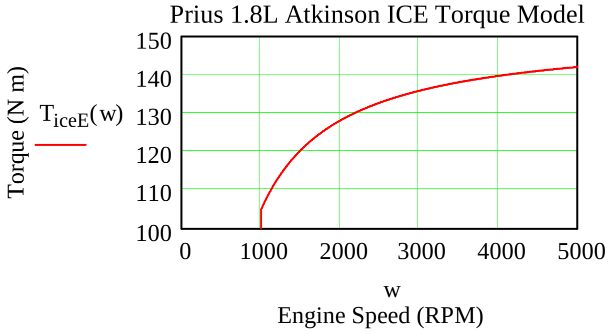
$$k := 1000 \quad T_{idle} := 85 \quad \Omega_{idle} := 1000 \quad P_{idle} := T_{idle}\cdot\left(\frac{2\cdot\pi\cdot\Omega_{idle}}{60\cdot k}\right) \quad P_{slope} := \frac{57 - P_{idle}}{4000} \quad T_{slope} := \frac{60.23 - P_{idle}}{4000}$$

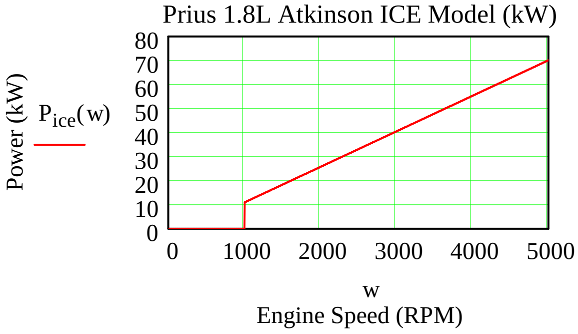
$$PIII_{ice}(w) := \text{if}\left[w < \Omega_{idle}, 0, P_{idle} + P_{slope}\cdot\left(w - \Omega_{idle}\right)\right] \quad TIII_{ice}(w) := \text{if}\left[w < \Omega_{idle}, 0, P_{idle} + T_{slope}\cdot\left(w - \Omega_{idle}\right)\right]\cdot\frac{60\cdot k}{2\cdot\pi\cdot w}$$

$$TIII_{ice}(w) := \text{if}\left(w > 5200, TIII_{ice}(5200), TIII_{ice}(w)\right) \quad PIII_{ice}(w) := \text{if}\left(w > 5200, PIII_{ice}(5200), PIII_{ice}(w)\right)$$

Scale Up to Gen IV Specs:

$$X_P := \frac{73}{57}\cdot\frac{73}{76} \quad X_T := \frac{142}{115} \quad P_{ice}(w) := PIII_{ice}(w)\cdot X_P \quad T_{iceE}(w) := TIII_{ice}(w)\cdot X_T$$





Model Equations for the Driveshaft, ICE, and Planetary Gears

Simulation of a Series Hybrid Electric Vehicle based on Energetic Macroscopic Representation

W. Lhomme1, A. Bouscayrol1, Member, P. Barrade2

$$J\cdot\frac{d}{dt}\Omega_{shaft} + f\cdot\Omega_{shaft} = T_{ice} - T_{dcg}$$

$$P_{ice} = m_{ice}\cdot k_{ice}\cdot\Omega_{shaft}$$

$$T_{ice} = m_{ice}\cdot k_{ice}\cdot dgas$$

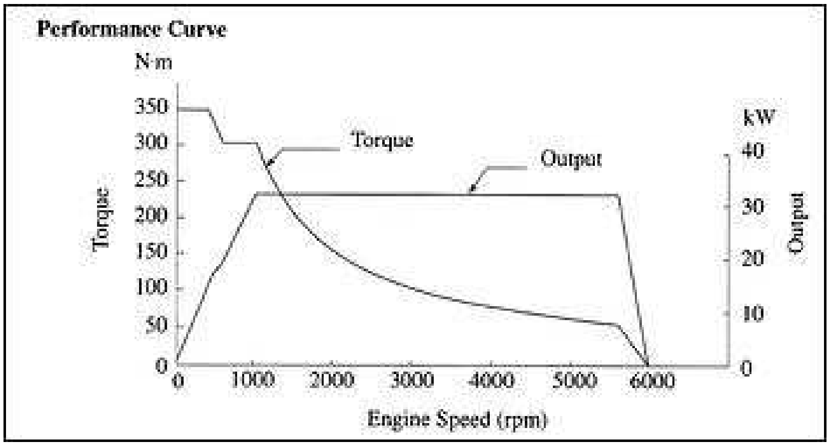
$$k_{ice} = \frac{\eta\cdot\rho\cdot P_c}{\Omega_{ice\_max}}$$

$$\omega_{mg1} + 2.6\cdot\omega_{mg2} = 3.6\omega_{ice}$$

J, f, and Ωshaft are the moment of inertia, friction coefficient, and speed of the shaft. Tice and Tdcg are the ICE and generator torques. The ICE pressure, Pice, results from the flow of gasoline. η is the ICE efficiency, ρ the density of gasoline, P_c the calorific value of gasoline and Ω_{ice_max} the maximum rotation speed of the engine. The control of the machine is ensured by the m_{ice} ratio, which defines the actual flow of gasoline, dgas, through a specific actuator.

The relation for the shaft rotational velocities ωice, ωmg1, and ωmg2 describes the action of the Hybrid Synergy Drive *Planetary Gear* (shown in the above illustration).

Gen III NHW20 MG2 Motor Performance Curves



Toyoto Prius Gen IV 1.8L-Vehicle, Motor and Road Parameters: **Specifications for Different Prius Models**

Gear Ratio and Efficiencies: $GR := 3.267$ $\eta_{inv} := 0.90$ $\eta_{eng\_axle} := 0.95$ $\eta_{axle} := 0.95$ $\eta_{eng\_m1} := 0.95$ $\eta_{red} := 0.95$

Max Motor Power: $Pmax_{m2} := 60 \cdot kW \cdot \eta_{axle}$ $Pmax_{m1} := 37 \cdot kW \cdot \eta_{eng\_m1}$ $Pmax_{ice} := 73 \cdot kW \cdot \eta_{eng\_m1}$

$Pmax_{m1} = 47.137\,hp$ $Pmax_{ice} = 93\,hp$

Max Motor Torque: $Tmax_{m1} := 207 \cdot ft \cdot lbf \cdot \eta_{eng\_m1}$ $Tmax_{ice} := 142 \cdot N \cdot m \cdot \eta_{eng\_m1}$

$Tmax_{m2} := 207 ft \cdot lbf \cdot GR_{m2} \cdot \eta_{axle}$

$r_{tire} := 0.287 \cdot m$ $RPM := min^{-1}$

Max Motor Speeds: **Max. Acceleration Mode==>** $\Omega max_{m1} := 9000 \cdot RPM$ $\Omega max_{ice} := 5200 \cdot RPM$

$Tmax_{m1} \cdot \Omega max_{m1} = 39.993\,kW$ Note MG1's power is speed (6500 rpm) limited

Set Pmaxbat to 0 for Extremum

$Redline := \Omega max_{ice} \cdot min$ $Tmax_{m2} = 702.815\,N \cdot m$ $Energy_{bat} := 6.5 \cdot kW \cdot hr$ $Pmax_{bat} := 27 \cdot kW$

Chasis and Environmental Parameters

Average Wind Velocity:	$Vw := 0 \cdot mph$	Frontal Area*:	$Afg := 2.33 \cdot m^2$
Shape Correction Factor:	$SCF := 0.85$	Frontal Area Corrected:	$Af := Afg \cdot SCF$ $Af = 1.98\,m^2$
Drag Coeff:	$Cd := 0.25$	Rolling Resistance Per Tire:	$RR_{tire} := 0.007$
Cross Wind Drag Coff:	$Cd_{cw} := 0.000014$	(Average 0% road grade)	$\theta := atan(0.0)$ θ (radians):
Air Density:	$\rho := 1.293 \cdot \frac{gm}{liter}$	Average Cross Wind:	$V_{cw} := 0 \cdot mph$
Road Rolling Resist:	$RR_{road} := 0.002$	Curb Weight:	$M_{curb} := 3042 \cdot lb$
Rotational Inertia Coeff:	$k_m := 1.08$	Passenger Weight:	$Passengers2 := 170 \cdot lb$
Gross Weight:	$M_{gross} := M_{curb} + Passengers2$	$M_{gross} = 3.212 \times 10^3\,lb$	$M_{batt} := 68 \cdot kg$

Vehicle Dynamics Equations - Find Velocity and Time for Maximum Acceleration

Road Resistance, Fr: $Fr(v) := M_{gross} \cdot g \cdot \left[\left(RR_{tire} + RR_{road} \right) \cdot \cos(\theta) + \sin(\theta) \right]$ $Fr(60 \cdot mph) = 128.589\,N$

Aerodynamic Loss, Fa: $Fa(v) := 0.5 \cdot \rho \cdot Af \cdot \left[(v + Vw)^2 \cdot Cd + Cd_{cw} \cdot (0.5 \cdot v + V_{cw})^2 \right]$ $Fa(60 \cdot mph) = 230.295\,N$

Opposing Force, Fo: $Fo(v) := Fa(v) + Fr(v)$ $Fo(60 \cdot mph) = 358.884\,N$ $Fo(60 \cdot mph) = 358.884\,N$

Velocity vs Shaft (MG2 Rotaional Speed) and Hybrid Synergy Gearing

$$M2rpm\_at\_mph(s) := \frac{GR \cdot s}{(2 \cdot \pi \cdot r_{tire} \cdot RPM)} \qquad velMG2\_at\_rpm(w) := \frac{2 \cdot \pi \cdot r_{tire} \cdot w \cdot RPM}{GR} \qquad v\_r(w) := \frac{2 \cdot \pi \cdot r_{tire} \cdot w \cdot RPM}{GR \cdot mph}$$

Control Strategies (Hybrid Synergy Drive Speed Relationships):
Develop an MG1 Profile and then Find Speed Relationships of MG2(ICE) and ICE(MG2)

Hybrid Synergy Drive
MG1 Control Stategy:
Max MG1 Rotation
Ωmax_{m1}
Initial M2 Spinup (Ωm1),
$\Omega 1init_{m2}(\omega_{mg2})$
and Driving Profiles,
$\Omega 1Prfl_{m1}$, $\Omega 1Prfl2_{m1}$

Max Acceleration Control Strategy P1: Turn on ICE at 15 mph (See Control Plot)

Apply maxium MG1 power/speed Ωmax_{m1} = 8500 RPM from Generator MG1 to MG2.

$$\Omega 1init_{m2}(\omega_{mg2}) := \text{if}\left(\omega_{mg2} < 700 \wedge Pmax_{bat} > 1\cdot kW, 1000 + \frac{\Omega max_{m1}}{820}\cdot\frac{\omega_{mg2}}{RPM}, \Omega max_{m1}\cdot min\right)$$

$$\Omega 1init_{ice}(\omega_{ice}) := \text{if}\left(\omega_{ice} < 1700 \wedge Pmax_{bat} > 1\cdot kW, 1000 + \frac{\Omega max_{m1}}{1950}\cdot\frac{\omega_{ice}}{RPM}, \Omega max_{m1}\cdot min\right)$$

$$\Omega 1Prfl_{m1}(\omega_{mg2}) := \Omega 1init_{m2}(\omega_{mg2})$$

Nominal Control Strategy P2: Constant ICE (rpm= 1800) to 60 mph, then ramp up. Profile 2- $\Omega 1Prfl2_{m1}$

Use just $\Omega_{ice\_vel}(vel)$ to find resultant relation between MG1 and Velocity, i.e. MG2

$$Vel_{rev\_up} := 60 \qquad \Omega_{ice\_vel}(vel) := \text{if}\left[vel < Vel_{rev\_up}, 1800, 1800 + (vel - Vel_{rev\_up})\cdot\frac{4000 - 1800}{100 - Vel_{rev\_up}}\right]$$

Calculate Control Point:
Rev up ICE from Cruise at
Vehicle Velocity Vel_{rev_up}
See Plot Lower Right

$$\Omega_{iceVel}(\omega_{mg2}) := \Omega_{ice\_vel}\left(\frac{velMG2\_at\_rpm(\omega_{mg2})}{mph}\right) \qquad \Omega_{iceVel}(5000) = 4.159\times 10^{3}$$

$$\Omega 1Prfl2_{m1}(\omega_{mg2}) := 3.6\cdot\Omega_{iceVel}(\omega_{mg2}) - 2.6\omega_{mg2}$$

Examination of above then gives us the form of $\Omega 1Prfl2_{vm1}(v)$

$$\Omega 1Prfl2_{vm1}(v) := \text{if}\left[v < 60, 6500 - \frac{7500}{60}\cdot v, -1000 + (v - 60)\cdot\frac{4000}{60}\right] \qquad xm2 := 1500$$

ICE and MG2 Rotation Profiles From MG1 Profiles Ω1Prfl1m1 (Enabled) or Ω1Pffl2m1 (Disabled):

$$\Omega_{ice}(\omega_{mg2}) := \frac{(\Omega 1Prfl_{m1}(\omega_{mg2}) + 2.6\cdot\omega_{mg2})}{3.6} \qquad \Omega_{mg2}(\omega_{ice}) := root\left(xm2 - \frac{\omega_{ice}\cdot 3.6 - \Omega 1Prfl_{m1}(xm2)}{2.6}, xm2\right)$$

$$\Omega_{ice}(\omega_{mg2}) := \frac{(\Omega 1Prfl2_{vm1}(v\_r(\omega_{mg2})) + 2.6\cdot\omega_{mg2})}{3.6} \qquad \Omega_{mg2}(\omega_{ice}) := root\left(xm2 - \frac{\omega_{ice}\cdot 3.6 - \Omega 1Prfl2_{vm1}(v\_r(xm2))}{2.6}, xm2\right)$$

Use these expressions Just for generating plots at bottom of page

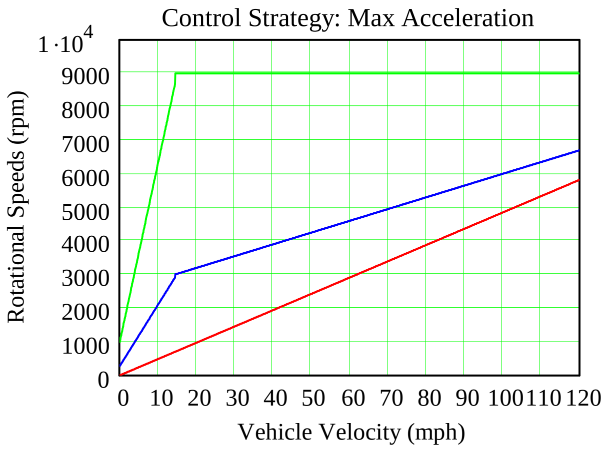
$$\Omega_{iceP1}(\omega_{mg2}) := \frac{(\Omega 1Prfl_{m1}(\omega_{mg2}) + 2.6\cdot\omega_{mg2})}{3.6} \qquad \Omega_{iceP2}(\omega_{mg2}) := \frac{(\Omega 1Prfl2_{vm1}(v\_r(\omega_{mg2})) + 2.6\cdot\omega_{mg2})}{3.6}$$

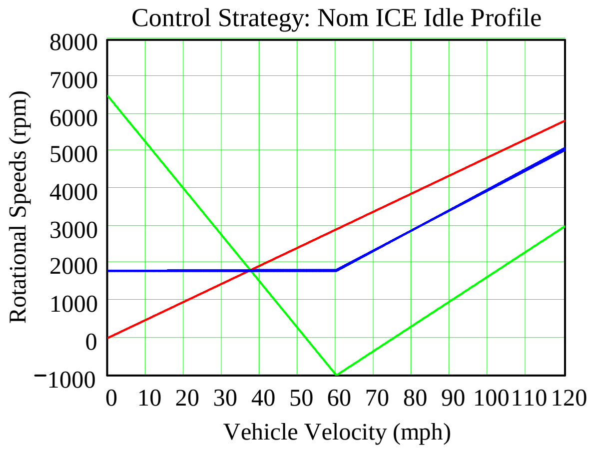
$$\Omega_{ice}(M2rpm\_at\_mph(120\cdot mph)) = 6.712\times 10^{3}$$

Control Stategy Plots: Max Acceleration and Nominal Cruise Profiles

Plot Colors: **MG2 Shaft Rotational Speed (Red)**, **ICE RPM (Blue)**, **and** **MG1 Rotor (Green)**.

Note Max Accel Plot: ICE does not turn on until MG2 propels Vehicle Speed up to 15 mph





Given Control Acceleration Stategy Ω1Prfl1m1: Calculate Power and Torque

Torque, ICE: $T_{icem2}(\omega_{mg2}) := T_{iceE}(\Omega_{ice}(\omega_{mg2}))\cdot N\cdot m$ $\Omega 1Prfl_{m1}(7000) = 9\times 10^{3}$

Torque,MG1: $T_{m1}(\omega_{mg2}) := -T_{icem2}(\omega_{mg2})\cdot 3.6^{-1}\cdot \eta_{eng\_m1}$

$$PinvA_{m2}(\omega_{mg2}) := \eta_{inv}\cdot(Pmax_{bat} - T_{m1}(\omega_{mg2})\cdot 2\cdot\pi\cdot\Omega max_{m1})$$

$$PinvB_{m2}(\omega_{mg2}) := \mathrm{if}(PinvA_{m2}(\omega_{mg2}) \ge Pmax_{m2}\cdot\eta_{inv}, Pmax_{m2}\cdot\eta_{inv}, PinvA_{m2}(\omega_{mg2}))$$

Max Power to Inverter: < P2max, P1max + Pbatmax and Pm1< P1max and Pice x 2.6/3.6

MG2 Inverter Power, Pinv:

$$Pinv_{m2}(\omega_{mg2}) := \mathrm{if}\left[-(T_{m1}(\Omega 1init_{m2}(\omega_{mg2}))\cdot 2\cdot\pi\cdot\Omega max_{m1}) > Pmax_{m1}, (Pmax_{bat} + Pmax_{m1})\cdot\eta_{inv}, PinvB_{m2}(\omega_{mg2})\right]$$

Torque MG2
Power Limited
Break Point, ω_{inv}

Problem, Find ω_{inv} such that:
$(Tmax_{m2})\ \omega_{inv} = Pinv_{m2}(\omega_{inv})$

Guess for winv, wx: $wx := \mathrm{if}(Pmax_{bat} < 1\cdot kW, 8, 800)$

$$\omega_{inv} := \mathrm{root}\left[Tmax_{m2} - \frac{Pinv_{m2}(wx)}{(2\cdot\pi wx + 1)\cdot RPM}, wx\right]$$

Solution (rpm): $\omega_{inv} = 759.842$

Torque, MG2: $T_{m2}(\omega_{mg2}) := \mathrm{if}\left(\omega_{mg2} \le \omega_{inv}, Tmax_{m2}, \dfrac{Pinv_{m2}(\omega_{mg2})}{2\cdot\pi\ \omega_{mg2}\cdot RPM}\right)$ $T_{m2}(\omega_{inv})\cdot 2\cdot\pi\ \omega_{inv}\cdot RPM = 55.923\,kW$

Tractive Torq, Total: $T_{tot}(\omega_{mg2}) := T_{m2}(\omega_{mg2}) + T_{icem2}(\omega_{mg2})\cdot\dfrac{2.6}{3.6}\cdot\eta_{eng\_axle}$ $P_{m2}(\omega) := T_{m2}(\omega)\cdot 2\cdot\pi\cdot\omega\cdot RPM$

Tractive Road Force, Total: $Ft\omega(\omega_{mg2}) := \dfrac{T_{tot}(\omega_{mg2})\cdot GR\cdot\eta_{red}}{r_{tire}}$

Tractive Road Force, Total: $F_{tot}(v) := \dfrac{T_{tot}(M2rpm\_at\_mph(v))\cdot GR\cdot\eta_{red}}{r_{tire}}$ $P_{M2}(\omega) := \dfrac{P_{m2}(\Omega_{mg2}(\omega))}{kW}$

Plot Terms: $P_{tot}(v) := F_{tot}(v)\cdot v$ $P_{tot}(60\cdot mph) = 108.955\,hp$

Applying maximum motor torque, find the velocity and time starting from initial velocity = 0 mph.

$End := 40$

Third Law of Motion:
(dv/dt is acceleration)

Given $\dfrac{d}{dt}v(t) = \dfrac{F_{tot}(v(t)) - Fo(v(t))}{k_m\cdot M_{gross}}$ $v(0) = 0$ $velocity := \mathrm{Odesolve}(t, End)$

$P_t(\omega_{m2}) := T_{tot}(\omega_{m2})\cdot 2\cdot\pi\cdot\omega_{m2}\cdot RPM\cdot kW^{-1}$

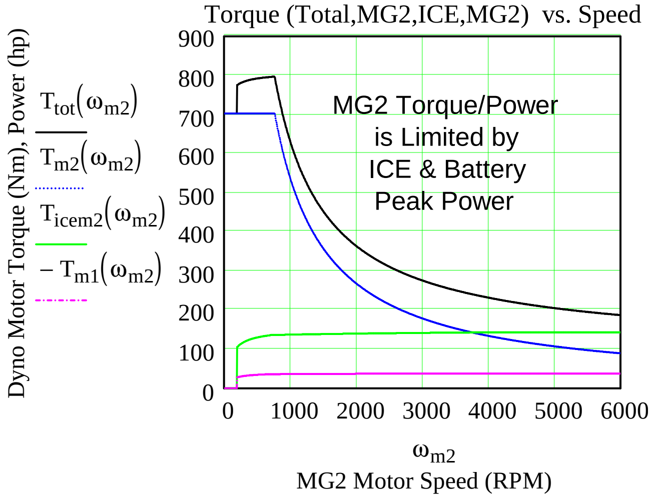
$$accel(t) := \frac{F_{tot}(velocity(t)) - Fo(velocity(t))}{k_m\cdot M_{gross}}$$

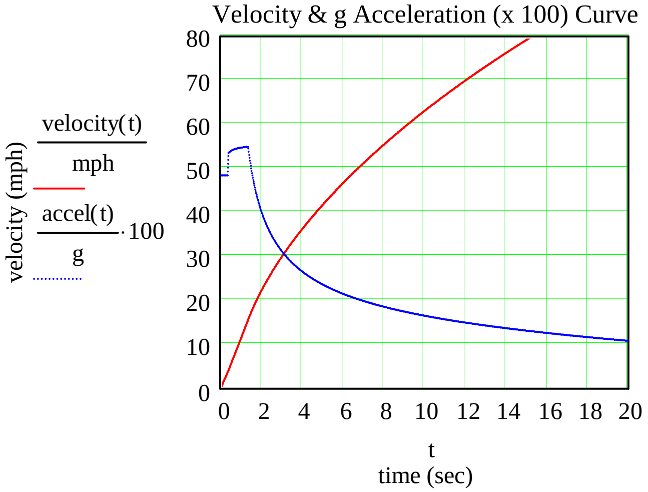
Prius Spec is 9.8 sec

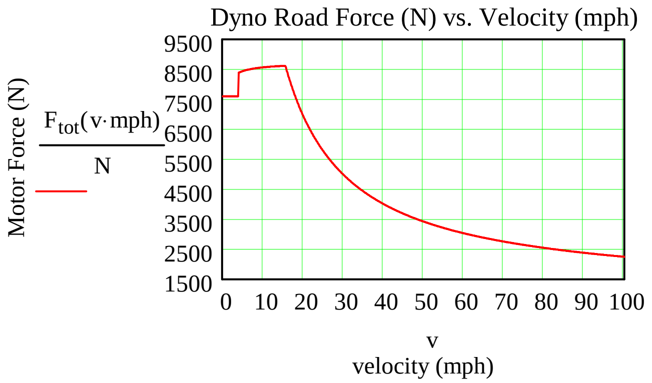
$Time := 0\cdot sec$ $time(v) := \mathrm{root}(v - velocity(Time), Time)$ $time(60\cdot mph) = 9.171\,s$

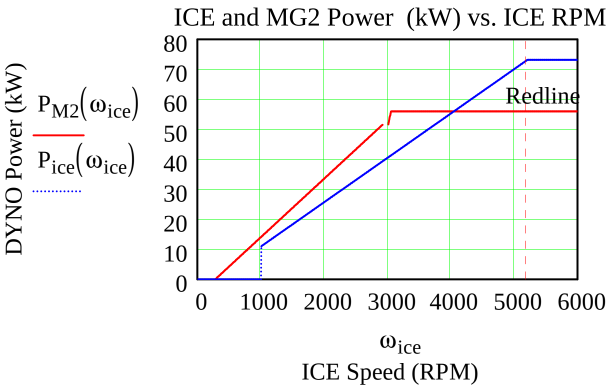
Passing 40 to 60 mph: $Passing := time(60\cdot mph) - time(40\cdot mph)$ $Passing = 4.495\,s$

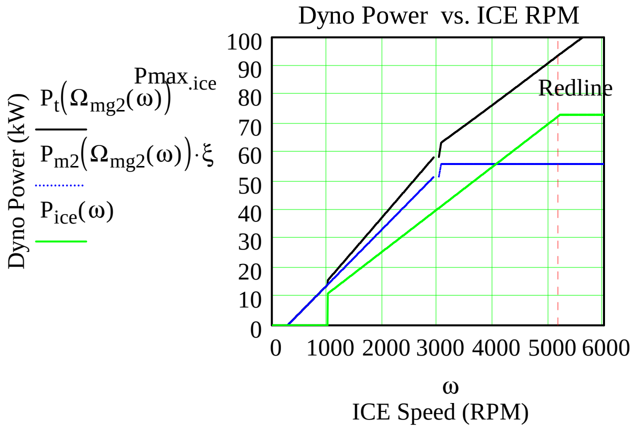
PRIUS GEN IV PEFORMANCE SIMULATION CURVES

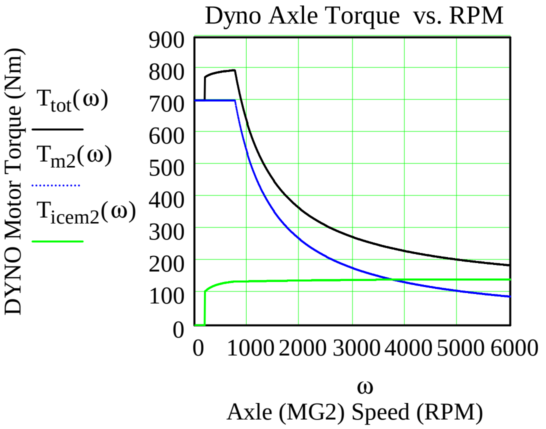


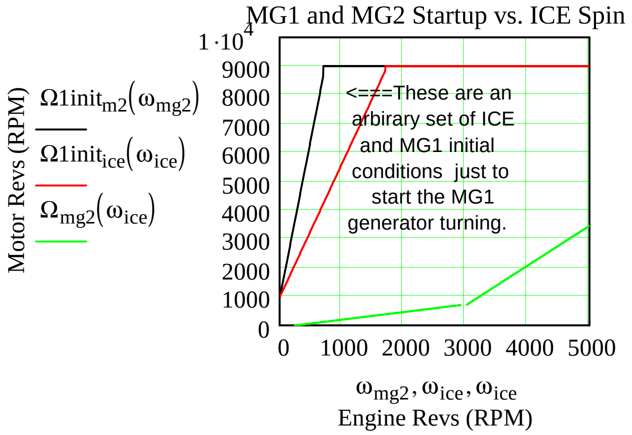


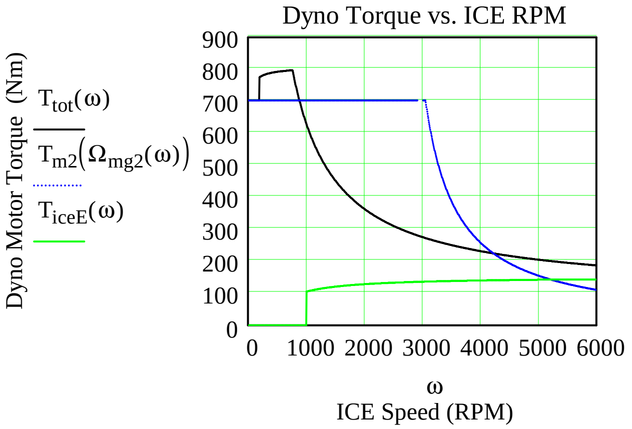












Find the Single Charge (@SOC = 50%) Cruise Range for a given Velocity

Driving Pattern/Profile:

Given we **cruise at constant speed** and Time for start, stop, and regen breaking, **Time_{ssr}= every 15 minutes**.

Drive Train Power Efficiency - Battery Loss to Force Commanded Vehicle Velocity:

State of Charge for generator is SOC_{gen}. **SOC_{gen} is 50% for recharge.** 201V HV battery **idle power is Po**. 12V battery gives Accessory Power. The Traction Inverter x motor Efficiency - TInvE, HV Power Electronics at Idle Efficiency - IPEE, and Gear Power Efficiency - GPE are 90%, 95%, and 97%, respectively. Brake Regen efficiency of kinetic energy is 69% @ deacceleration = 0.315g. Then the number of starts per hour as a function of velocity, NS, NumStarts(v, Po), is

$\text{Time}_{ssr} := 30\text{min} \quad \text{TInvE} := 0.90 \quad \text{IPEE} := 0.95 \quad \text{GPE} := 0.97 \quad \text{Regen} := 0.69 \quad \text{SOC}_{gen} := 0.5$

$$\text{Power}_{dissLoss}(v, P_o) := \frac{\text{Fo}(v)\cdot v}{\text{TInvE}\cdot\text{GPE}} + \frac{P_o\cdot\text{watt}}{\text{IPEE}}$$

USABC Round Trip Battery Energy Efficiency

$\text{RTEff} := 0.92$

$\text{Energy}_{accel}(v) := \text{Pmax}_{m2}\cdot\text{time}(v)$

NSo and NS are iterative converging estimates of NumStarts

$$\text{NS}_o(v) := 2\cdot\left(\frac{50\cdot\text{mph}}{v}\right)^2 \qquad \text{NS}(v, P_o, S) := \frac{\text{Energy}_{bat}\cdot(1-S) - \text{NS}_o(v)\cdot\left(\frac{\text{Energy}_{accel}(v)}{\text{TInvE}\cdot\text{GPE}} - \frac{\text{Regen}\cdot M_{gross}\cdot v^2}{2}\right)}{\text{Power}_{dissLoss}(v, P_o)\cdot\text{Time}_{ssr}}$$

$$\text{NumStarts}(v, P_o, S) := \text{floor}\left[\frac{\text{Energy}_{bat}\cdot(1-S) - \text{NS}(v, P_o, S)\cdot\left(\frac{\text{Energy}_{accel}(v)}{\text{TInvE}\cdot\text{GPE}} - \frac{\text{Regen}\cdot M_{gross}\cdot v^2}{2}\right)}{\text{Power}_{dissLoss}(v, P_o)\cdot\text{Time}_{ssr}}\right]$$

$$\text{Cruise\_Range}(v, P_o, S) := \frac{\left[\text{Energy}_{bat}\cdot(1-S) - \text{NumStarts}(v, P_o, S)\cdot\left(\frac{\text{Energy}_{accel}(v)}{\text{TInvE}\cdot\text{GPE}} - \frac{\text{Regen}\cdot M_{gross}\cdot v^2}{2}\right)\right]\cdot v}{\text{Power}_{dissLoss}(v, P_o)}$$

Single Charge Highway Cruise Range Estimate

$\text{Cruise\_Range}(30\cdot\text{mph}, 50, \text{SOC}_{gen}) = 32.869\,\text{mi}$

$\text{Cruise\_Range}(40\cdot\text{mph}, 50, \text{SOC}_{gen}) = 26.844\,\text{mi}$

$\text{Cruise\_Range}(50\cdot\text{mph}, 50, \text{SOC}_{gen}) = 21.842\,\text{mi}$

$\text{Cruise\_Range}(55\cdot\text{mph}, 50, \text{SOC}_{gen}) = 19.591\,\text{mi}$

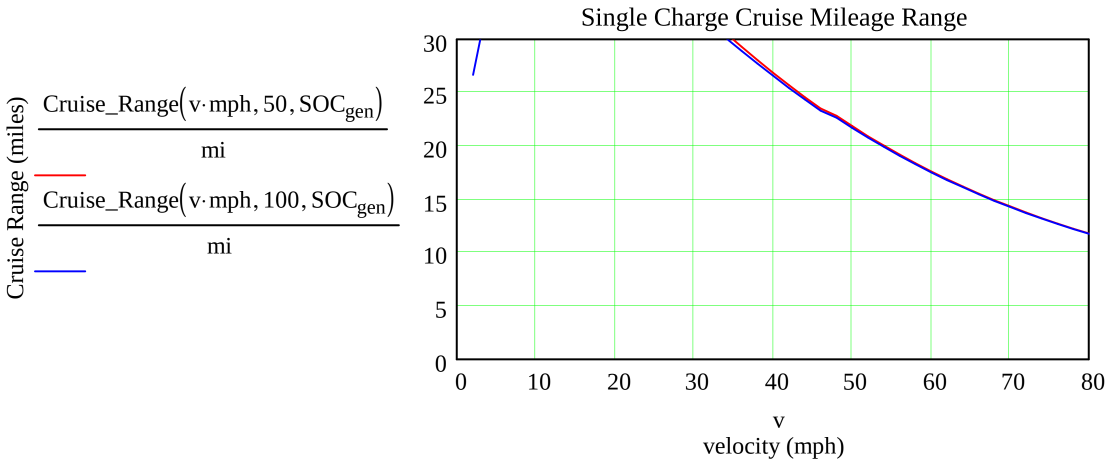
$\text{Cruise\_Range}(60\cdot\text{mph}, 50, \text{SOC}_{gen}) = 17.601\,\text{mi}$

$\text{Cruise\_Range}(62.5\cdot\text{mph}, 50, \text{SOC}_{gen}) = 16.697\,\text{mi}$

$\text{Cruise\_Range}(70\cdot\text{mph}, 50, 0.5) = 14.31\,\text{mi}$

Velocity Range

$v := 0, 2 .. 80$



Cruise Range as a Function of Traction Battery Idle Power, Po

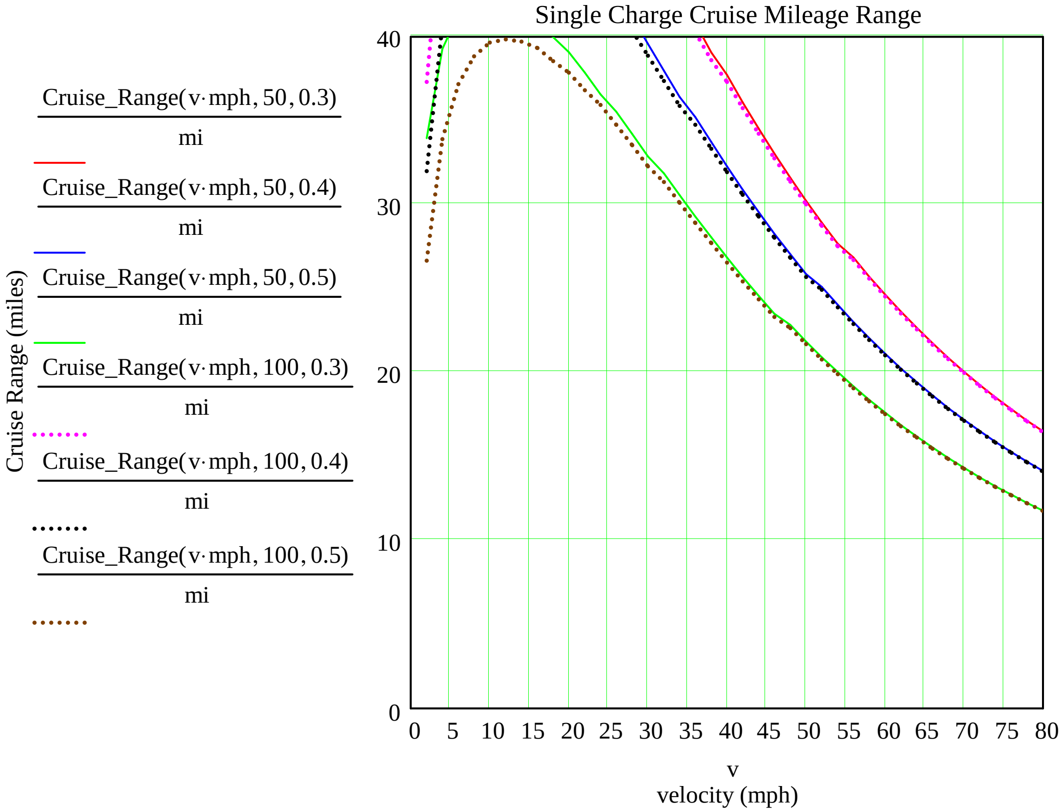
$$\text{Cruise\_Range}(15\cdot \text{mph}, 50, 0.3) = 57.727\,\text{mi}$$

$$\text{Cruise\_Range}(55\cdot \text{mph}, 50, 0.5) = 19.591\,\text{mi}$$

$$180\cdot\frac{\text{km}}{\text{hr}} = 111.847\,\frac{\text{mi}}{\text{hr}}$$

$$\frac{0.5 - 0.25}{0.5} = 0.5$$

$$\frac{\text{Cruise\_Range}(55\cdot \text{mph}, 100, 0.25) - \text{Cruise\_Range}(55\cdot \text{mph}, 100, 0.5)}{\text{Cruise\_Range}(55\cdot \text{mph}, 100, 0.5)} = 0.482$$



Find the Power to Maintain Constant Velocity

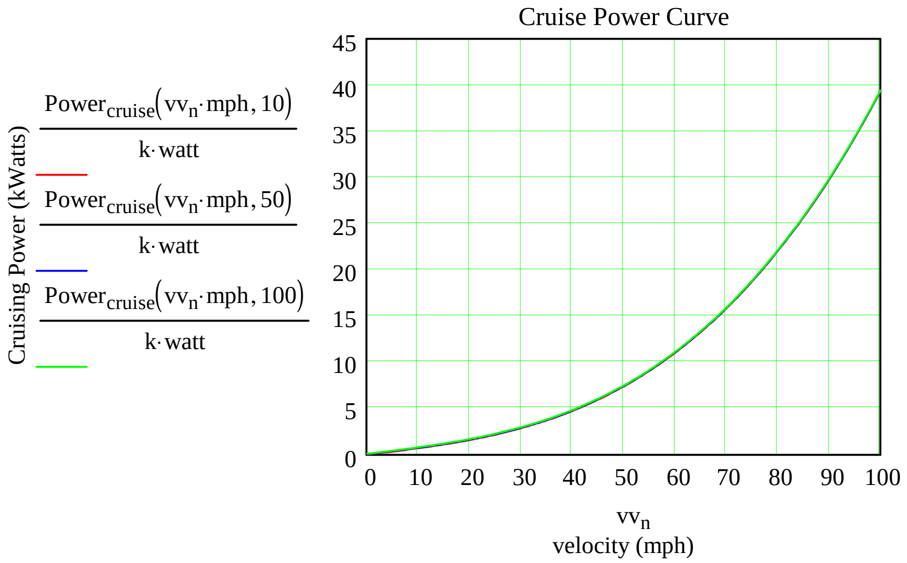
Note: The generator's output is 54 kW. This allows it produce a net charge up to 80 mph cruise.

$$\mathrm{Power}_{\mathrm{cruise}}\left(v, P_o\right) := \mathrm{Power}_{\mathrm{dissLoss}}\left(v, P_o\right)$$

$$\mathrm{Power}_{\mathrm{cruise}}(60\cdot \mathrm{mph}, 100) = 11.132\,\mathrm{kW}$$

$$n := 0 .. 200 \qquad \tau_n := \frac{n}{10} \qquad w_n := \frac{n}{20} \qquad vv_n := \frac{n}{2}$$

$$P_{\mathrm{cruise}_n} := \frac{\mathrm{Power}_{\mathrm{cruise}}\left(vv_n\cdot \mathrm{mph}, 100\right)}{k\cdot \mathrm{watt}}$$



FTPF := READPRN("http://www.leapcad.com/Transportation/FedTestProc.TXT")

UDDSF := READPRN("http://www.leapcad.com/Transportation/uddscol.txt")

HWYF := READPRN("http://www.leapcad.com/Transportation/hwycol.txt")

FP10 := READPRN("http://www.leapcad.com/Transportation/FTP10Hz.TXT")

HY10 := READPRN("http://www.leapcad.com/Transportation/HWY10Hz.txt")

US06F := READPRN("http://www.leapcad.com/Transportation/US06PROFILE.TXT")

AER Given Three Different Driving Schedules

Read US06 and FTP Driving Profile Files
http://www.epa.gov/nvfel/testing/dynamometer.htm

The US06 cycle represents an 8.01 mile (12.8 km) route with an average speed of 48.4 miles/h (77.9 km/h), maximum speed 80.3 miles/h (129.2 km/h), and a duration of 596 seconds.
The Federal Test Procedure(FTP) is composed of the UDDS followed by the first 505 seconds of the UDDS. It is often called the EPA75. FP10 is a 10 Hz Sampling. HY10 is the 10 Hz Highway schedule.

$$tx := FTPF^{\langle 0\rangle} \qquad FTP := FTPF^{\langle 1\rangle} \qquad \mathrm{rows}(FTP) = 1.875\times 10^{3}$$

$$UDDS := UDDSF^{\langle 1\rangle} \quad \mathrm{rows}(UDDS) = 1.37\times 10^{3}$$

$$HWY := HWYF^{\langle 1\rangle} \qquad R_{hwy} := \mathrm{rows}(HWY)$$

$$FTP10V := \mathrm{submatrix}(FP10, 0, \mathrm{rows}(FP10) - 1, 1, \mathrm{cols}(FP10) - 1)$$

$$HWY10V := \mathrm{submatrix}(HY10, 0, \mathrm{rows}(HY10) - 1, 1, \mathrm{cols}(HY10) - 1)$$

$$time := US06F^{\langle 0\rangle} \qquad US06 := US06F^{\langle 1\rangle} \qquad n_6 := 0 .. 598$$

All Electric Range, AER, for Driving Profile Velocity/Time File, P Sampling Rate, Hz, and SOC = 0

Regen Efficiency Curve vs Decel (g): $\mathrm{REff}(g) := \frac{85}{77}\cdot 0.01\cdot\left[\left(1 - e^{-27.129\cdot g}\right)\cdot 91.235 - 28.408\right]$ $\quad Gg := \frac{mph}{sec\cdot g}$

```
AER(P,Hz) :=
    $Ebat \leftarrow E_{diss} \leftarrow v_{old} \leftarrow 0$
    $n \leftarrow -1$
    $N \leftarrow \mathrm{rows}(P) - 1$
    while $E_{diss} < \frac{Energy_{bat}}{kW\cdot hr}$
        $n \leftarrow n + 1$
        $t \leftarrow \mathrm{mod}(n, N)$
        $v \leftarrow P_t$
        $v_{avg} \leftarrow (v + v_{old})\cdot 0.5$
        $P_{accel} \leftarrow \frac{k_m\cdot M_{gross}\cdot (v - v_{old})\cdot\frac{mph\cdot Hz}{sec}\cdot v_{avg}\, mph}{TInvE\cdot GPE}$  if $v > v_{old}$
        $P_{accel} \leftarrow k_m\cdot M_{gross}\cdot (v - v_{old})\cdot\frac{mph\cdot Hz}{sec}\cdot v_{avg}\, mph\cdot \mathrm{REff}\left[(v_{old} - v)\cdot Hz\cdot Gg\right]$  otherwise
        $E_{diss} \leftarrow E_{diss} + \frac{\left(Power_{dissLoss}(v\cdot mph, 100) + P_{accel}\right)\cdot sec}{kW\cdot hr\cdot Hz}$
        $v_{old} \leftarrow v$
        $Ebat_n \leftarrow E_{diss}$
    $R \leftarrow \sum_{m=0}^{n} \frac{\left(P_{\mathrm{mod}(m,N)} + P_{\mathrm{mod}(m+1,N)}\right)\cdot mph\cdot sec}{2\cdot mi\cdot Hz}$
    $R$
```

$r1 := 0 .. \mathrm{rows}(HY10)\cdot 10 - 1$ $\qquad HWY10_{r1} := HWY10V_{\mathrm{ceil}\left(\frac{r1+1}{10}\right)-1,\, \mathrm{mod}(r1, 10)}$

$\mathrm{AER}(US06, 1) = 22.039$ $\qquad \mathrm{AER}(FTP, 1) = 33.524$ $\qquad \mathrm{AER}(HWY, 1) = 33.053$ $\qquad \mathrm{AER}(HWY10, 10) =$

EPA 20085 Cycle MPG Fuel Economy Least Squares Fit Regression for AER to SOC = 0

$MPG_{city} := \frac{1}{\left(0.003259 + \frac{1.18053}{\mathrm{AER}(FTP, 1)}\right)}$ $\quad MPG_{city} = 25.992$ $\qquad MPG_{hwy} := \frac{1}{0.001376 + \frac{1.3466}{\mathrm{AER}(HWY, 1)}}$ $\qquad X := \frac{1}{40}$

$MPG_{epa} := 0.55\cdot MPG_{city} + 0.45\cdot MPG_{hwy}$ $\qquad MPG_{epa} = 24.98$

$r := 0 .. \mathrm{rows}(FTP) - 1$ $\quad Distance_r := \sum_{r=0}^{r} FTP_r\cdot\frac{10}{60\cdot 60}$ $\qquad rr := 0 .. \mathrm{rows}(US06) - 1$ $\quad Distance._{rr} := \sum_{rr=0}^{rr} US06_{rr}\cdot\frac{10}{60\cdot 60}$

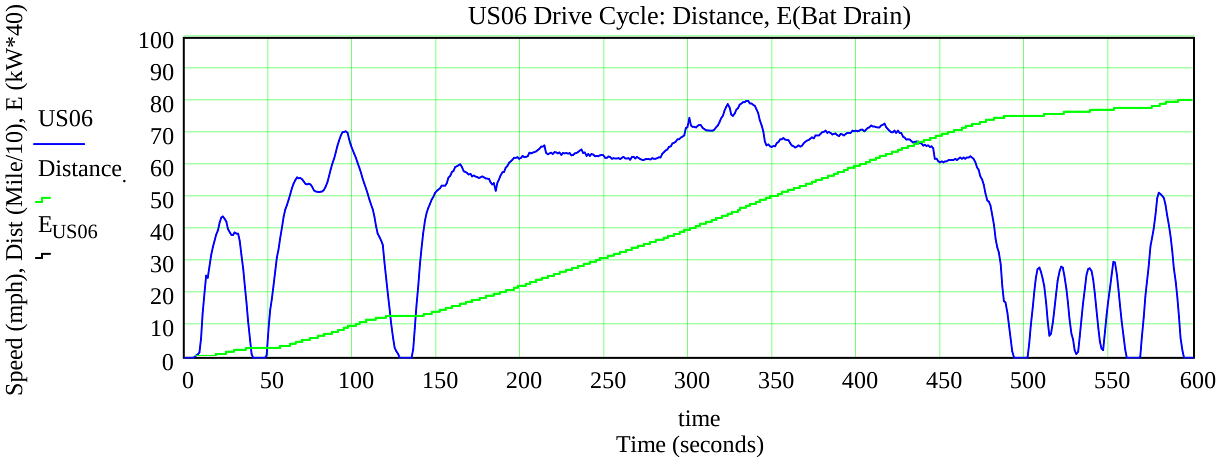
$\max(Distance) = 110.41$ $\qquad \max\left(Distance_.\right) = 80.08$

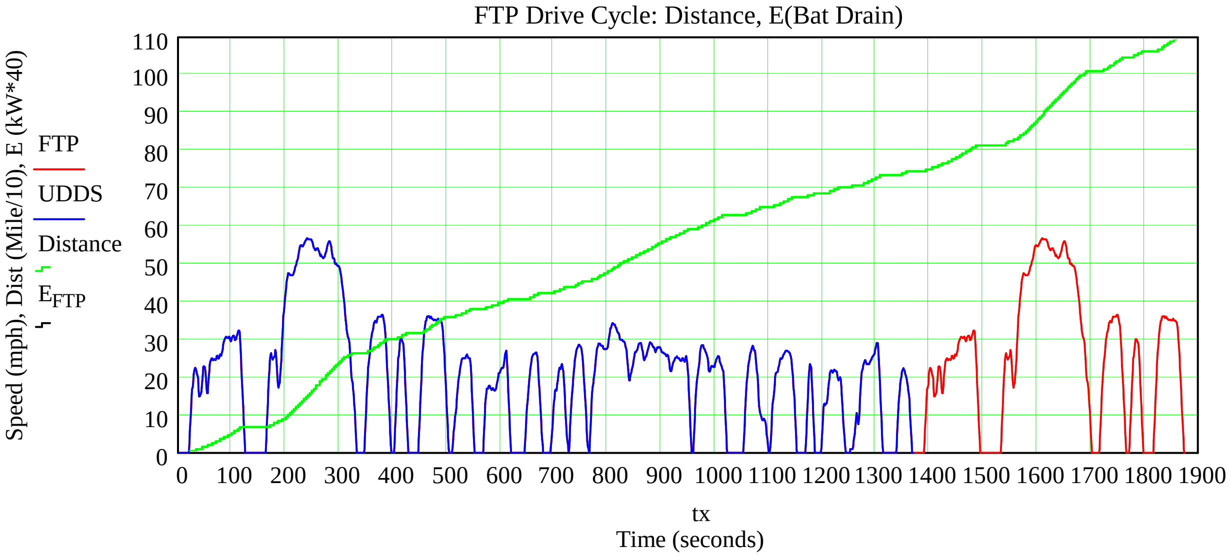
SAVE PROFILES

$\mathrm{WRITEPRN}(\text{"EFTP.PRN"}) := \mathrm{AER}(\mathrm{FTP},1)\cdot 40$ $\quad E_{FTP} := \mathrm{READPRN}(\text{"EFTP.PRN"})$ $\quad \max(E_{FTP})\cdot X = 27.275$

$\mathrm{WRITEPRN}(\text{"EUS06.PRN"}) := \mathrm{AER}(\mathrm{US06},1)\cdot 40$ $\quad E_{US06} := \mathrm{READPRN}(\text{"EUS06.PRN"})$ $\quad \max(E_{US06})\cdot X = 19.263$

$\mathrm{WRITEPRN}(\text{"EHWY.PRN"}) := \mathrm{AER}(\mathrm{HWY},1)\cdot 40$ $\quad E_{HWY} := \mathrm{READPRN}(\text{"EHWY.PRN"})$ $\quad \max(E_{HWY})\cdot X = 26.8$





Read Charge Depletion Mode Data

$Volt := READPRN(\text{"Volt\_tVelwMAgTPmFP.prn"})$

Read Charge Sustaining Mode Data (**Disabled**)

$Volt := READPRN(\text{"VoltSus\_tVelwMAgTPmFP.prn"})$

$Volt := READPRN(\text{"VoltGenOnly\_tVelwMAgTPmFP.prn"})$ $\qquad PT(v) := \frac{P_{tot}(v \cdot mph)}{hp}$

$cols(Volt) = 10$ $\qquad n := 0..300$ $\qquad P_{tot}(v) := F_{tot}(v \cdot mph) \cdot v \cdot mph \cdot hp^{-1}$

$time_v := Volt^{\langle 0 \rangle}$ $\quad v_v := Volt^{\langle 1 \rangle}$ $\quad \omega_v := Volt^{\langle 2 \rangle} \cdot k$ $\quad mph_v := Volt^{\langle 3 \rangle}$ $\quad g_v := Volt^{\langle 4 \rangle}$ $\quad tz_n := \frac{n}{10}$

$q := (N \cdot m)^{-1}$ $\quad T_v := Volt^{\langle 5 \rangle}$ $\quad P_v := Volt^{\langle 6 \rangle}$ $\quad F_v := Volt^{\langle 7 \rangle}$ $\quad Pv_v := Volt^{\langle 8 \rangle}$ $\quad P_{cruiseV} := Volt^{\langle 9 \rangle}$

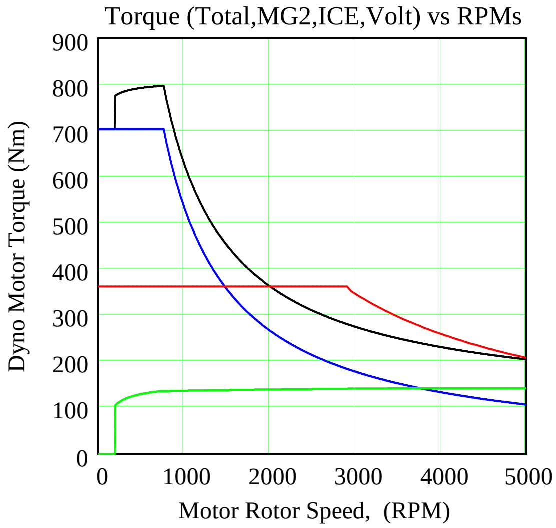
$\omega_{x_n} := \frac{6000 \cdot n}{200}$ $\quad Ttot_n := T_{tot}\left(\omega_{x_n}\right) \cdot q$ $\quad Tm2_n := T_{m2}\left(\omega_{x_n}\right) \cdot q$ $\quad Tice_n := T_{icem2}\left(\omega_{x_n}\right) \cdot q$ $\quad Vx_n := velocity\left(tz_n\right)$

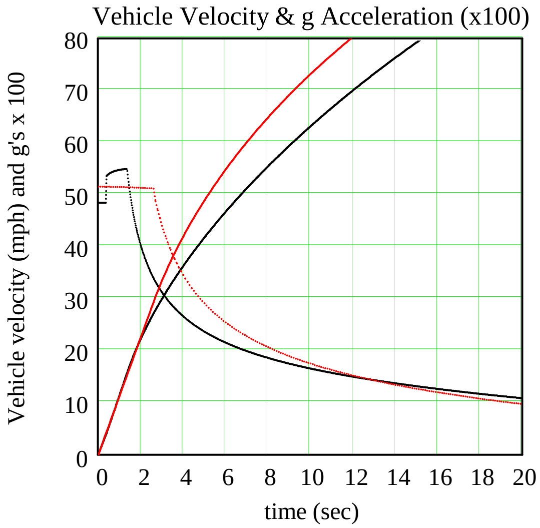
$Ax(Vx) := \frac{\left(F_{tot}(Vx \cdot mph) - Fo(Vx \cdot mph)\right) \cdot 100}{k_m \cdot M_{gross} \cdot g}$ $\quad ax_n := Ax\left(Vx_n\right)$ $\quad Ft_n := \frac{F_{tot}\left(Vx_n \cdot mph\right)}{N}$ $\quad Pt_n := \frac{P_{tot}\left(Vx_n \cdot mph\right)}{hp}$

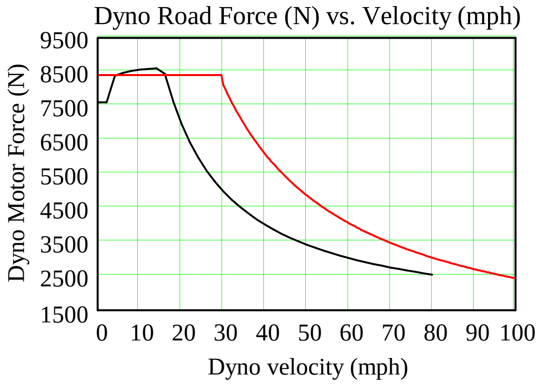
$PreWtTotM2ICVA := augment\left(\omega_x, tz, Ttot, Tm2, Tice, Vx, ax, Ft, Pt\right)$ $\quad WRITEPRN(\text{"Pre3PB0.txt"}) := PreWtTotM2ICVA$

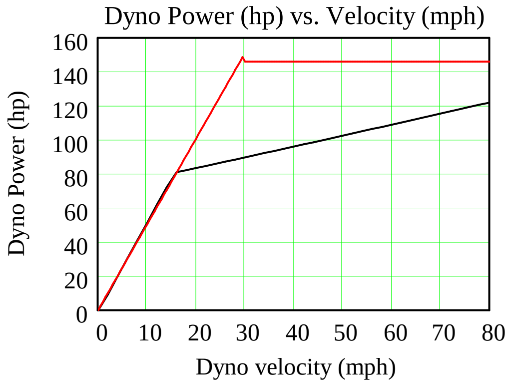
2010 Prius (Black) vs. Sustaining Mode Volt (Red) Acceleration Performance

Volt Power reduced from 111 kW to Generator Power x 90% = 47.7 kW in Sustaining Mode.
Volt 0 to 60 mph time increases from 8.5 to 15 seconds.
Volt 40 mph to 60 mph Sustaining passing time increased from 3.3 seconds to **8.5 seconds**.









Read Comparison Files Either for GenIV No Battery Power or Full Power Gen III Prius

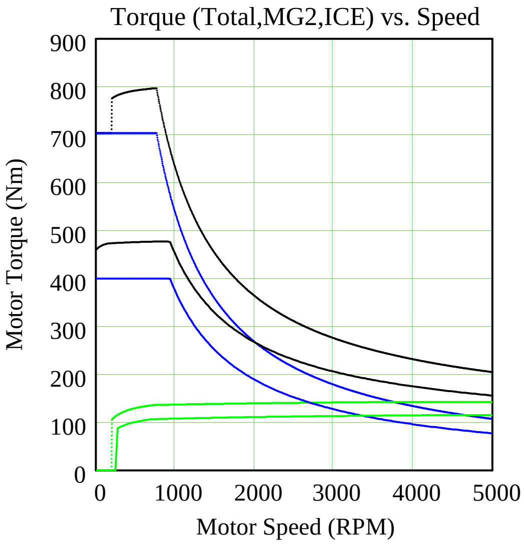
Pre := READPRN("Pre3PB0.txt")   Pre := READPRN("PreGenIII.txt")   PreWtTotM2ICVA

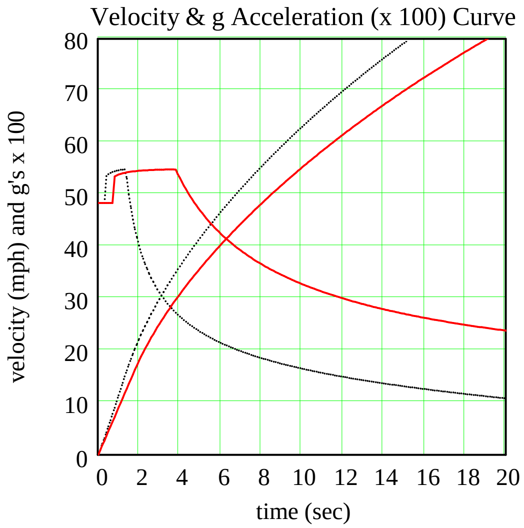
$\omega_z := Pre^{\langle 0 \rangle}$ $time_z := Pre^{\langle 1 \rangle}$ $Ttotz := Pre^{\langle 2 \rangle}$ $Tm2z := Pre^{\langle 3 \rangle}$ $Ticez := Pre^{\langle 4 \rangle}$ $Vz := Pre^{\langle 5 \rangle}$ $az := Pre^{\langle 6 \rangle}$

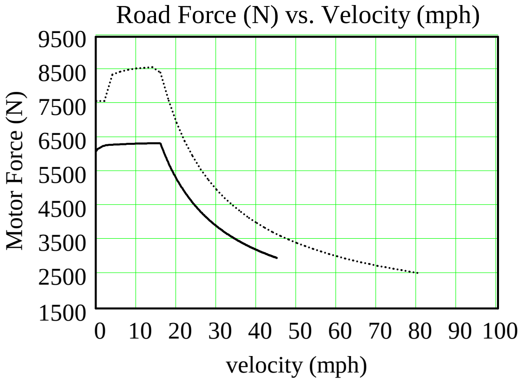
$Fz := Pre^{\langle 7 \rangle}$ $Pz := Pre^{\langle 8 \rangle}$ $Agx(t) := \frac{accel(t)}{g}$

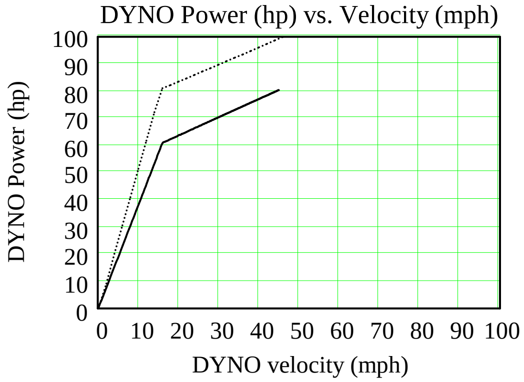
Comparison Prius Gen III (Sold) vs. Prius Gen IV (Dotted)

Comparison Prius No Battery (Solid) vs. Battery (Dotted)

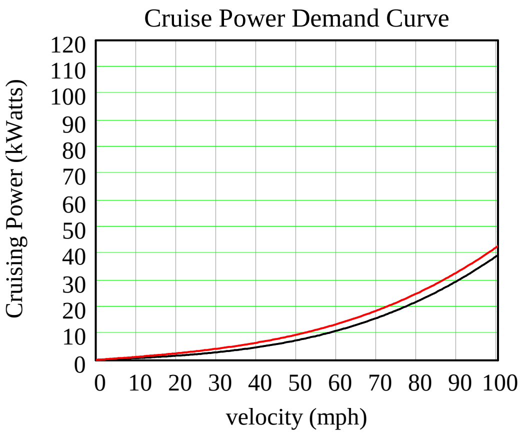








$Fuel\_Use := READPRN("http://www.leapcad.com/Transportation/Prius\%201\_5L\%20Atkinson\%20Fuel\%20Use.TXT")^{T}$



Switch Solid and Dotted Curves

Comparison Prius No Battery (Dotted) vs. Battery (Solid)

Comparison Prius Gen III (Dotted) vs. Prius Gen IV (Solid)